City of Greeley

NATURAL GAS HAZARD POTENTIAL

City of Greeley

October, 1984

INTERNATIONAL ENGINEERING COMPANY, INC.
A MORRISON-KNUDSEN COMPANY

AMUEDO and IVEY, INC.

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CONSULTING
ENGINEERS

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October 17, 1984

Mr. Sam Sasaki
Assistant City Manager
City of Greeley
917 7th Street
Greeley, CO 80631

SUBJECT: Gas Hazard Study, Greeley, Colorado

Dear Mr. Sasaki:

Transmitted herewith is our report describing the investigation of the potential hazard to the City of Greeley from natural gas which might be vented to the surface of the ground. While we used a generalized approach to the problem, much of the data as well as the conclusions are petroleum-related. This is because the purpose of the investigation was to determine whether a safety problem exists due to oil and gas drilling. Secondly, the problem is primarily geological, and the bulk of subsurface geological data was derived fron information gained in petroleum development.

Direct information needed to arrive at solid conclusions is not available for reasons explained in the report. Very little data have been generated on the "1100-foot Sandstone" which we consider vital to the problem. Our conclusions are therefore strongly influenced by professional judgment. Partly for this reason we have recommended some further investigations, ongoing data collection, and continual monitoring of known gas vents.

The maps on which the geologic data are presented are reproduced full-sized in the report. These maps should be continually updated as new data are made available.

We appreciate the cooperation and assistance we received from you and others on the City staff. Personnel of the Fire Department and the Museum were of particular help as well as was the Weld County Health Department.

If you have any questions regarding the report, we will be happy to discuss them with you.

Sincerely,

Robert C. Bolger

Robert C. Bolger
Project Manager

RCB:ap
Enclosures: a/s

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I. INTRODUCTION

Background

From 1881 to 1886 Greeley, Colorado underwent a boom with the drilling of wells to about 1275 feet in the search for potable water. These wells were used for an undetermined period, and with the passage of time most of them were forgotten. Today little is known of them, other than from newspaper accounts. In early 1984 a series of events in the Town of LaSalle, about four miles to the south, gave new potential meaning to these old wells in Greeley.

In early February 1984, natural gas was found emitting at the surface of the ground in the town of LaSalle. The immediate source was found to be an abandoned, covered water well. An attempt was made to control the gas, after which gas was vented at still another point and an explosion and fire resulted. As a consequence of the incident and because of the proximity of LaSalle, the City of Greeley retained International Engineering Company, Inc. (IECO) and its subcontractor, Amuedo and Ivey, Inc. (A&I), to "determine whether a safety problem exists from oil and gas drilling within the city limits of Greeley, Colorado, and if so, devise remedial or preventive methods, if possible."

The assignment originally covered only the area within the Greeley Comprehensive Plan. Subsequent to the contract signed in late May, the study was expanded from about 70 to 220 square miles (see Figure 1). The work plan included gathering data from existing sources - the literature, government agencies, oil companies, and private parties - to construct maps and sections to depict the geological setting and relationships in the area. Those data and a review of the LaSalle happenings were then to be used in an attempt to explain the mechanisms possibly responsible for the LaSalle incident and to relate them to the Greeley area. Little field work was anticipated owing to the short time and limited budget for the study. This report describes the investigations carried out under the assignment and the conclusions derived from it.

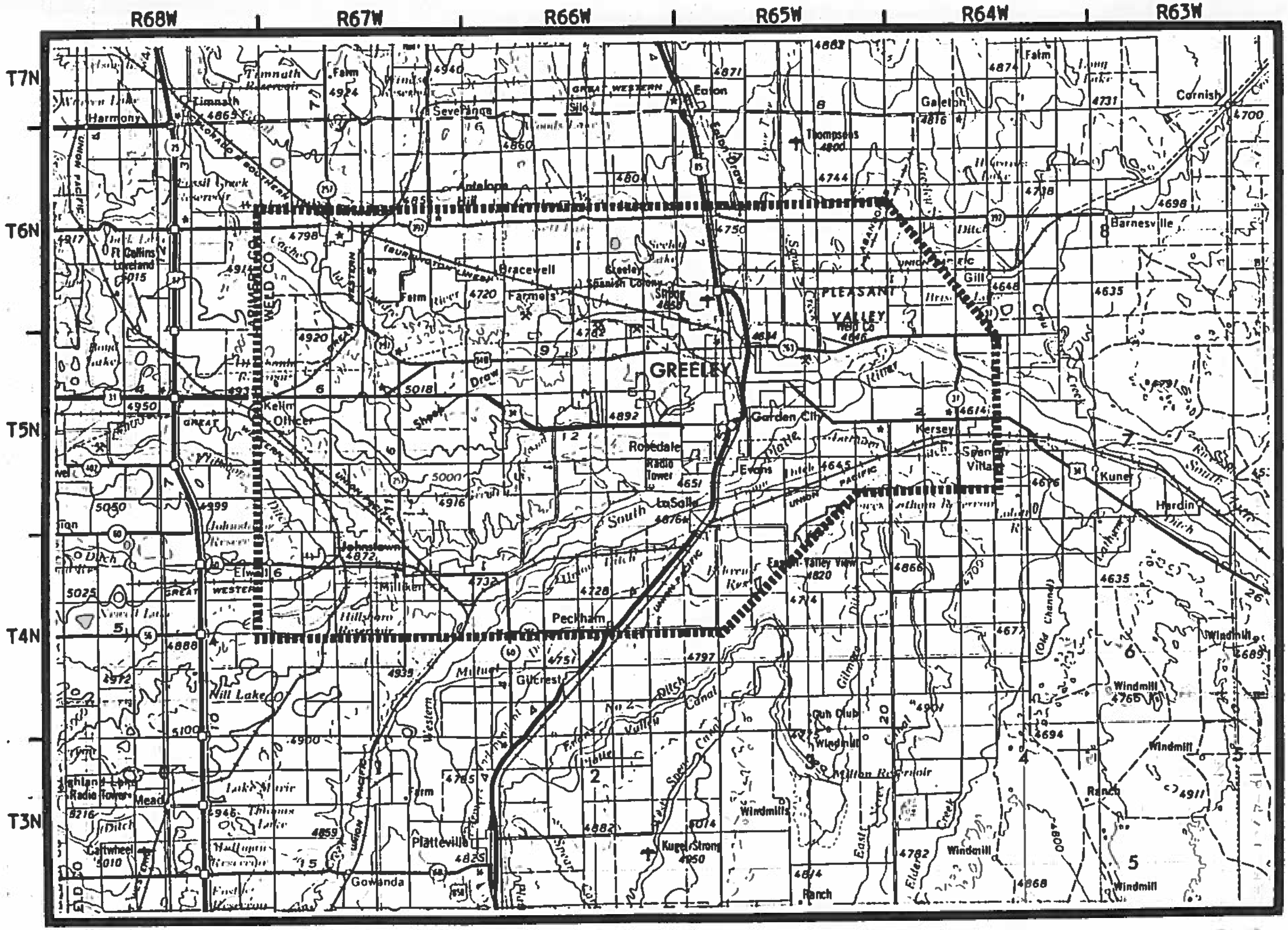


Figure 1 Regional location map showing area of investigation
scale 1"=3.95 miles

The LaSalle Incidents

On the evening of February 9, 1984, an apparent explosion was heard and felt in the area about two blocks from the Wickes lumber yard in the center of LaSalle. The local police and fire departments were alerted and they searched for the source without success throughout the night. Some residents attributed the incident to a sonic boom or possibly an earthquake.

The next day, an employee of Wickes Lumber Company noted that the blacktop in the parking area back of the yard had buckled and gas was being vented through the pavement. The area was excavated and a four-inch well casing was found covered by three to four feet of fill. The well, identified as Wickes #1, was blowing water and gas; it was plugged, but not probed. The work was completed at 5:00 p.m. on February 17. At 2:00 a.m. on February 18, an explosion and fire occurred in the lumber yard about 200 feet west of Wickes #1 and a second abandoned well, Wickes #2, was found.

About two weeks after the explosion, a crack was observed in the pavement of the United Bank across the street from the lumber yard. Excavation revealed another four-inch well casing. Still another abandoned well was found beneath the foundation on the west side of the United Bank building, but little gas was emitted from that well.

Gas samples from the Wickes #1 well and the United Bank #1 were analyzed and found to be similar to that found in the Codell Sandstone in the Wattenberg gas field. One notable exception was the presence of an anomalous amount of carbon dioxide in the gas.

On June 17, 1984, a LaSalle fireman noticed gas and water bubbling at the surface of the ground under the water tower about 750 feet east of the Wickes #1 well. The area was excavated and an abandoned well was found in a concrete box about 5 x 8 feet in size and six feet in depth. Gas was being emitted from the well, and later analysis indicated that it originated in the Codell. The minutes of the Town Board of Trustees meeting on February 16, 1917 contain a contract to drill a water well at that site to a depth of 1100 feet. This site had been checked for methane gas during the earlier investigation at LaSalle, but no gas was found at or near the site.

As of September 28, gas was still being vented from the Wickes #1, the United Bank #1, and the water tower well; no gas was found in the shallow vent pipes, and no further events have occurred as of this writing (9/28/84).

Potential Problems in Greeley

The similarity of conditions at LaSalle and at Greeley point up the potential for problems to arise in the Greeley area. There has been oil and gas drilling to the Codell within the city and further drilling permits had been applied for at the time of the first LaSalle event. At least eight water wells are known to have been drilled within the city limits to a depth approximating the LaSalle water tank well and the assumed depth of Wickes #1. One water well is recorded as having been drilled about 2700 feet deep. Newspaper accounts in the late 1800s described flowing wells from a depth of about 1100 feet to 1475 feet which produced "carbonic acid" (carbon dioxide). Also recorded was a black oily substance, which was said not to be petroleum.

Thirty-seven oil or gas wells had been drilled within the area enclosed by Greeley city limits prior to the first LaSalle event. Permit applications had been made for 11 more but these had not been drilled. Of the existing wells, nine were in recently annexed areas so that no records were on file with the City.

The geology at the two municipalities is essentially the same. The surface has a mantle of gravel, underlain by the Fox Hills aquifer. Below the Fox Hills is the thick Pierre Shale which includes at least five prominent sandstone units; there is little structural relief on these sandstones and their composition is similar. Some variation exists in shale unit thickness, but the sandstones generally are laterally persistent. Below the shale is the Niobrara Formation and the Benton Group which includes the Codell Sandstone. Gas is produced from the Codell after hydraulic fracturing in both the LaSalle and Greeley areas.

The conditions and gas occurrence are so similar that the City imposed a moratorium on further petroleum development on March 9, 1984. The moratorium was successively extended until May 1, when the regulations were

changed by the City to require surface casing to be cemented from the surface to a depth of 3000 feet. That regulation was further amended on August 17 to provide for stage cementing as required by the Colorado Oil and Gas Conservation Commission (COGCC), for mud logging to detect gas zones, and for cementing those zones in which hydrocarbons are found.

Study Authorization

On March 20, 1984, IECO was requested by the City to submit a proposal to perform the studies necessary to quantify the potential danger in Greeley. The proposal was submitted on March 21 and an interview with Greeley officials and representatives of other interested governments was held on April 18. IECO was notified on April 25 that they had been selected for the study, and a contract was signed on May 30, 1984. Subsequently, the scope of the work was enlarged and a change order was issued on August 27, extending the period of time as well as further enlarging the scope of work.

II. DATA COLLECTION

Literature Search

Various publications including those from the United States Geological Survey, Colorado Geological Survey, and the Colorado School of Mines were reviewed to acquire information pertaining to this project. These publications are listed in the Selected References section of this report.

General Contacts

Contact was established and meetings were held with state and local government agencies, oil companies, petroleum consultants, and private parties. The purpose of this effort was to determine as many as possible of the factors which related to the potential that a gas hazard could exist in Greeley and vicinity. As a practical matter, this liaison effort continued throughout the project, and several meetings were held with some parties. Frequent liaison was established with City officials in Greeley during the investigation.

The logical starting point for this investigation was to determine what had been done at LaSalle, and to apply the findings there to the definition of the potential problem in Greeley. The first contacts were with the Colorado Geological Survey, the Colorado Oil and Gas Conservation Commission, the Office of the State Engineer, and officials in the LaSalle town government. Meetings were held to discuss the findings of previous investigations and to gather basic geological, oil-and-gas well, and water-well data for the area. After the basic data-gathering process got underway, oil and gas operators, petroleum consultants, the U.S. Geological Survey, and oil service companies were contacted to acquire specific information on practices and procedures utilized in drilling, completing, and maintaining oil and gas wells in the area.

The third main area of contact was established with individuals who might be aware of historical drilling activity and the development of water wells within Greeley and its vicinity. Much of the critical information needed related to water wells which had been drilled in Greeley in the early to middle 1880s.

All of the contacts established were important to the successful execution of this project, and certain of them were critical. The critical ones were those that specifically had to do with the LaSalle events, and with oil and gas well development and regulation in the area.

Specific Contacts

A meeting was arranged with Mr. John Rold, State Geologist and Director, Colorado Geological Survey (CGS), to determine the findings of his study of the February 1984 event at LaSalle. In our investigation we have generally referred to this information as the LaSalle model. The field investigation by the CGS was complete by the time of our meeting. Mr. Rold generously described his investigation in LaSalle since a formal report had not been prepared at the time of our initial contact.

Mr. William R. Smith, Director, Colorado Oil and Gas Conservation Commission, was contacted to determine what regulations exist on drilling, completing, and operating oil and gas wells. The Commission staff has been involved in a regional gas-pressure monitoring program since shortly after the February 1984 event in LaSalle. That region includes the area of the investigation for Greeley. Data from this investigation have been made available to us. The Commission files containing oil and gas well logs and related data also have been made available to us.

Mr. John C. Romero, Chief, Ground Water Analysis Branch, Office of the State Engineer, provided information relating to groundwater studies underway in the vicinity of, and including, the Greeley area. Data from records of over 2000 water wells in the State Engineer's files were examined in the course of our investigation.

Bellwether Exploration Company was contacted because of its extensive oil and gas drilling activity including permit applications for wells to be drilled in the City. Messrs. George Aubrey, Tony Sharp, Chuck Fowler, and Roger Hively provided information on oil-well completion practices in the area, as well as geological data.

Mr. Thomas B. Majors, Petroleum Consultant for the Town of LaSalle, provided information on activities at LaSalle, and in the general Greeley- LaSalle area.

Other contacts established during the period of this investigation are noted and credited in appropriate places in the text of this report. It should be noted that this phase of the investigation was extremely important. The type of information needed for the investigation was not available from a single source. Many apparently unrelated facts had to be assimilated to develop reasonable conclusions.

III. DATA ASSIMILATION

Geologic Map

The general surface geology is shown on Plate 1. This map is a compilation and modification of maps prepared by Shelton and Rogers (1983), Colton (1978), and Hershey and Schneider (1972). The map shows the general distribution of rock formations and unconsolidated alluvial materials. The Pierre Formation Transition Zone is mapped on the western side of the project area. This rock unit dips gently eastward and is overlain by the Fox Hills Sandstone which in turn is overlain by the Laramie Formation. A series of alluvial and colluvial deposits including recent river and stream detritus, terraces, and fans covers most of the bedrock outcrops in the area.

In the subsurface the Pierre Formation includes a number of sandstone members. These are from the surface downward (Figure 2), the "1100-foot", the Richards (Greeley), Parkman (Larimer or Rocky Ridge), Sussex (Terry), and Shannon (Hygiene) Sandstones. The terms in parentheses are also used by some workers to identify these sandstones. Beneath the Pierre Shale, at a depth of about 7000 feet, is the Niobrara Formation, and immediately below that is the Codell Sandstone which is of primary interest because gas from it has been found in water wells in LaSalle and vicinity.

Gas also occurs in the Richards, Parkman, Sussex, and Shannon Sandstones in the project area, and in other areas along the Front Range.

Oil and Gas Well Data

Oil and gas well data were collected from the Petroleum Information Corporation's (PI) well log library, the COGCC files, published literature, and private sources. A base map showing the type and location of the oil and gas wells in the project area was compiled from the COGCC township plats which were copied June 15, 1984, and PI's Colorado Regional Amman Base Map Number 23, dated June 4, 1984. The base map compiled was used for all of the plates in this report. A number adjacent to a well on the base map indicates that a completion card is on file for the well or that information for the well was obtained from a well log.

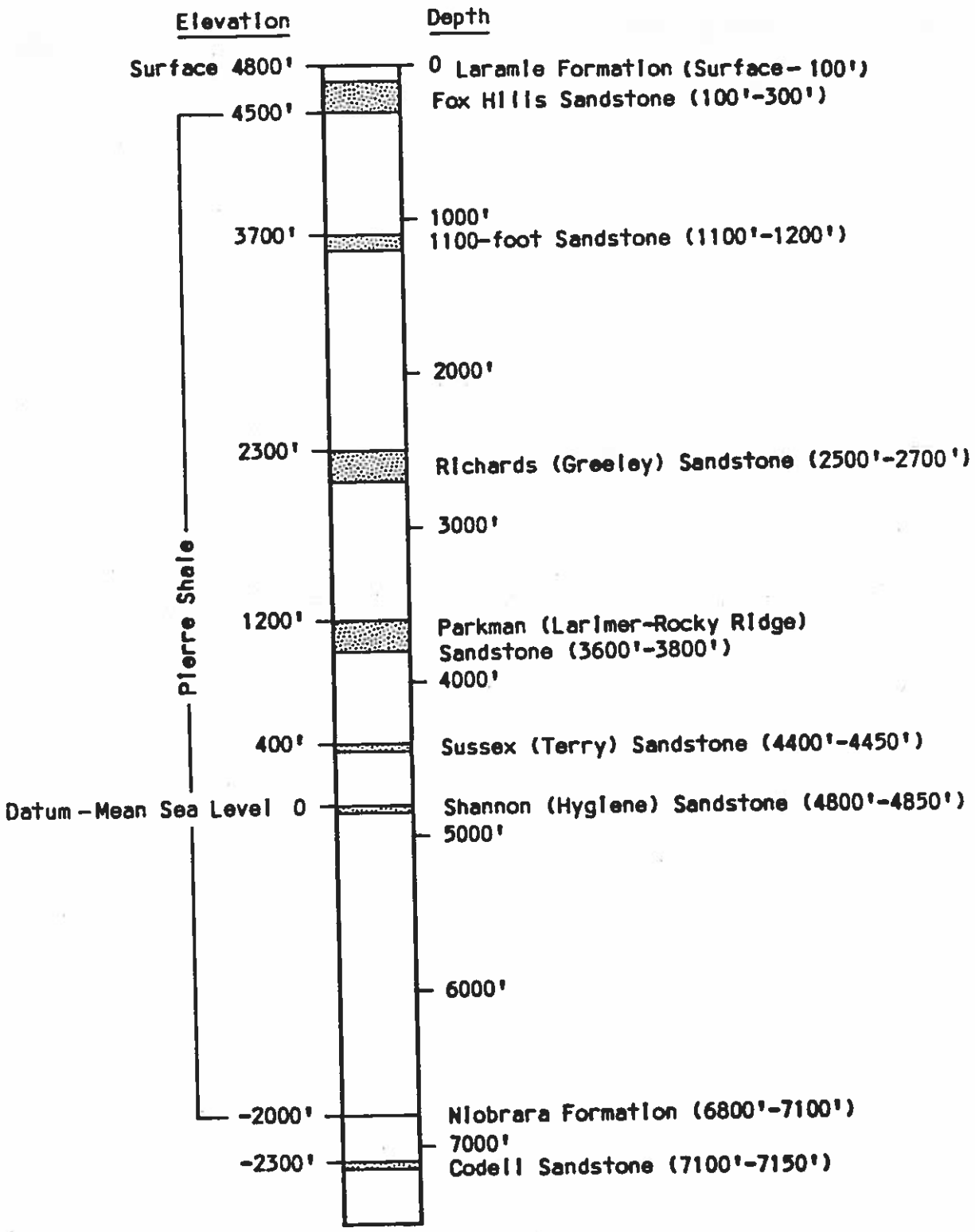


Figure 2 Representative Stratigraphic Section

scale 1"=1000'

Initially, well completion cards (a total of 510) were copied at the PI library and reviewed. Formation tops recorded on the cards were assimilated and plotted on the base maps. Not all cards, however, had formation tops posted. Electric logs were reviewed to pick formation tops not included on the cards and to check questionable data. It was not within the scope of work for this project to review every well log available within the project area; however, efforts were made to acquire enough data to provide a representative data base. All available electric logs of oil wells within the Greeley city limits were purchased from PI.

Structure Contour Maps (Plates 2 through 7)

Available elevations on mapping units were compiled for each major continuous sandstone unit overlying and including the Codell Sandstone. These sandstones above the Codell, in ascending order, are the Shannon Sandstone, Sussex Sandstone, Parkman Sandstone, Richards Sandstone, and the 1100-foot Sandstone. Neither the top nor the base of the Fox Hills Sandstone (the base of which is about 800 feet above the top of the 1100-foot Sandstone) could be established from geophysical logs since the surface casing was set through the Fox Hills in all but a few wells. Drillers' logs from water wells were inconclusive as to the upper and lower boundaries of the Fox Hills. After the data base for each of the sandstone mapping horizons was established, structure contours, with 50-foot intervals, were drawn on the top of each horizon.

Cross Sections (Plates 9 and 10)

Cross sections through the investigation area were developed to illustrate the nature of the subsurface geology. Cross section A-A' (Plate 9) includes nine wells used for control and trends east-west through Greeley and the area of investigation. Cross section B-B' (Plate 9) trends north-south through Greeley and the center of the investigation area and includes 10 wells for control. Geophysical logs of the wells included in these cross sections were purchased from PI so that they could be carefully examined with respect to subsurface correlations.

Four additional cross sections were prepared to interpret and illustrate the subsurface geology along the area of relatively steeper dip in the western part of the area of investigation. These cross sections, C-C', D-D', E-E', and F-F', are on Plate 10.

Water Well Data

Data printouts were acquired from the State Engineer's Office for the water wells in the area of investigation to determine the locations and depth of water wells. Of a total of just over 2000 water wells, only five wells were determined to be 500 feet or greater in depth. These wells were plotted on the structure contour map of the 1100-foot Sandstone (Plate 2). Each of these five wells was visited in the field.

Information was reviewed that was compiled by personnel of the Greeley Natural History Museum regarding eight deep artesian wells drilled in the city of Greeley in the 1880s (see Table 1). Records for these wells were not found in the State Engineer's Office, but research indicated that they were drilled to depths ranging from 1100 feet to over 1400 feet and penetrated the 1100-foot Sandstone. The locations of these wells are shown on Figure 3.

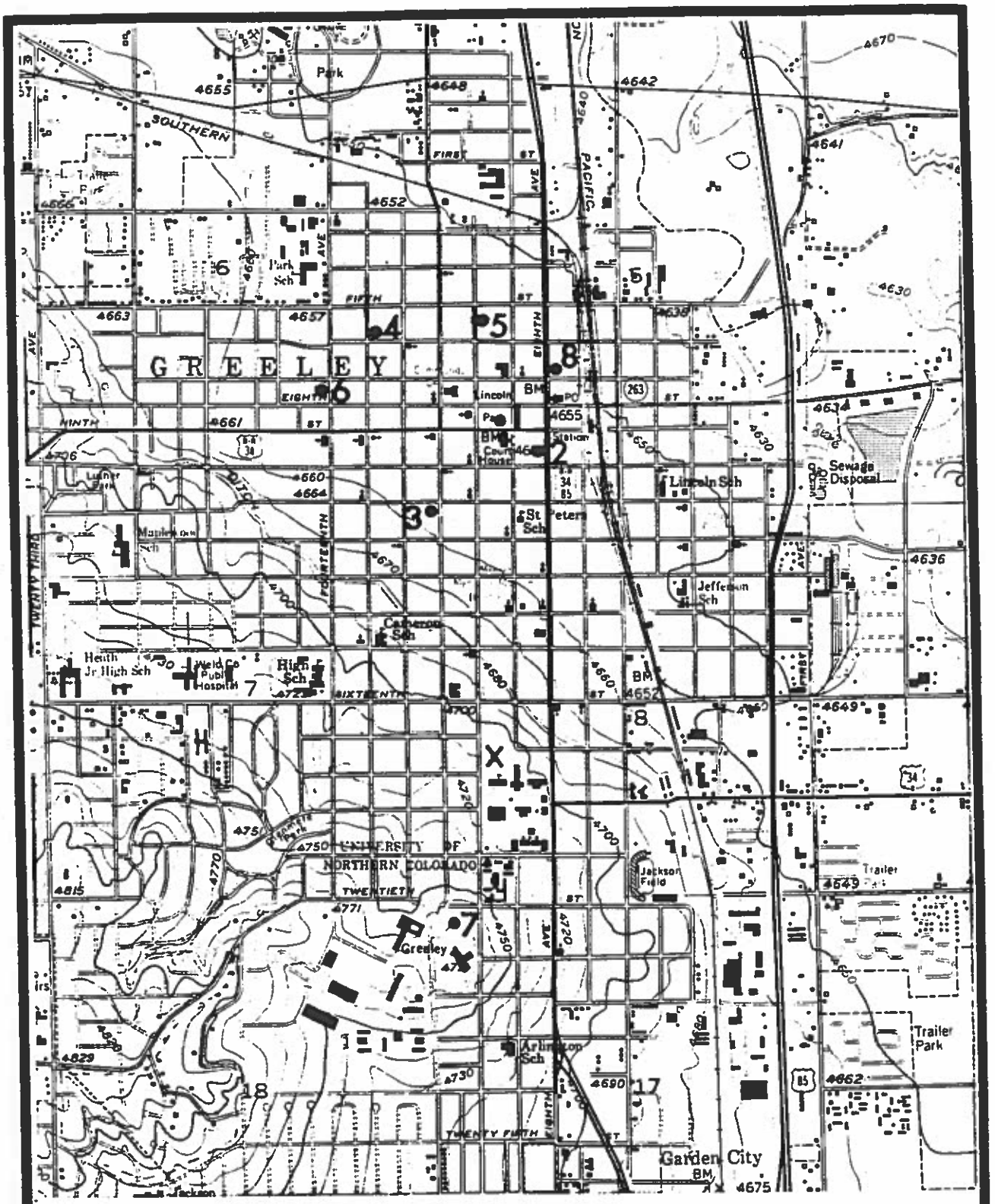
A historical account in The Greeley Tribune (5/28/1884, Greeley Municipal Museum) of artesian well No. 1, drilled during 1883 and 1884, in Lincoln Park, indicates that the well was completed at a depth of 1475 feet and that a water-bearing sandstone 25 feet to 30 feet thick was encountered at a depth of 1170 feet. It was later reported that a flammable gas (methane?) flowed from the well before it was abandoned. Mr. John Dugan (personal communication, 8/2/84), in researching the history of Weld County, found accounts of gas having been flared at this well.

The Colorado School of Mines Quarterly, Volume 41, No. 1 (January 1946) includes data on two deep wells drilled in Greeley. One was drilled in the early 1870s somewhere in SW 1/4 Sec 6, T5N, R65W to a depth of 2700 feet, and produced artesian water and flammable gas.

Artesian Well No.	Date Completed	Depth Drilled (ft)	Depth to Water Bearing Sandstone (ft)	Location
1	April 1884	1475	1170	South Lincoln Park
2	September 1884	unknown	1100	8th St public parking lot 8 (8th Ave between 9th St & 10th St)
3	May 1886	unknown	unknown	SW corner of 11th St & 11th Ave
4	May 1886	1200+?	1150	School grounds at 13th Ave & 6th St
5*	June 1886	1287	1160	514 10th Ave
6*	July 1886	1200+?	unknown	1402 7th St
7	unknown	unknown	unknown	University Center lawn 10th Ave & 20th St
8	unknown	unknown	unknown	NW corner of 8th Ave & 7th St

*Wells found and sampled; other wells not found.

Table 1. ARTESIAN WELL DATA



T5N R65W

Figure 3 Artesian well location map

scale 1"=2000'

Another well was drilled to a depth of 2200+ feet and produced gas, but the account says nothing of its flammability. It is located somewhere in T5N, R65W; the date it was drilled is unknown. Reference is also made to five other artesian wells presumably drilled in the Greeley area, but no locations or other data are given.

The five water wells deeper than 500 feet and the eight artesian wells with known general locations were visited in the field at various times during the months of August and September 1984. See Plate 2 for the locations of the five wells which are deeper than 500 feet. The purpose of these field visits was to more accurately locate the wells, to check for the presence of methane, and to take samples of water and gas. An Explosimeter Model 2A combustible gas indicator belonging to the Greeley Fire Department was used to check for methane at reported well locations.

Water well No. 1, located in NW 1/4 NW 1/4 Sec 11, T5N, R66W, on the Greeley Country Club property, was drilled in 1961 to a depth of 500 feet. The well was abandoned about 10 years ago and it is believed to be underneath a portion of the men's locker room. Methane was not detected around the clubhouse.

Water well No. 2, located in NW 1/4 SW 1/4 Sec 28, T6N, R65W, was drilled to a depth of 504 feet in 1962. The well is presently being used as a source of domestic water. Methane was not detected at the well.

Water well No. 3, located in NW 1/4 NE 1/4 Sec 27, T6N, R65W, was drilled to a depth of 593 feet in 1962. The well is still open but has not been pumped in five or six years. Methane was not detected coming from the well.

Water well No. 4, located in SW 1/4 SW 1/4 Sec 2, T5N, R67W, was drilled to a depth of 800 feet in 1978. It appeared that the well was set up for pumping. Methane was not detected around the well site.

Water well No. 5, located in SE 1/4 NE 1/4 Sec 19, T6N, R64W, was drilled in 1959 to a depth of 575 feet. The well is no longer in service and methane was not detected. The depth to water on September 4, 1984 was 55 feet below ground level.

Artesian well No. 1, located in southern Lincoln Park, is beneath the stone monument erected in 1907. Apparently the well is plugged and capped. Historical accounts indicate that this well released flammable gas along with water before it was shut down. Readings were taken with the methanometer around and under the monument, around the perimeter of the concrete walkway surrounding the monument, and in the grass surrounding the walkway. Methane was not detected.

Artesian well No. 2 is probably located under what is now a paved parking lot (8th Street public parking lot #8) at 8th Avenue between 9th Street and 10th Street. Readings were taken where possible around the site and methane was not detected.

Artesian well No. 3 is located at the southwest corner of the intersection of 11th Street and 11th Avenue. The well is most likely situated on the southern half of the lot. A Direct Sales tire store now occupies the site. A representative of the store's district office researched the files on the store dating back 20+ years, but found no evidence of a well. Readings were taken in and around the shop and along cracks in the pavement with no shows of methane.

Artesian well No. 4 is believed to be located somewhere on the grounds of what is now the Head Start School at 13th Avenue and 6th Street. City and County employees contacted were not familiar with the well. A former school district employee, who began working for the district in 1927 and who was familiar with the area, had no recollection of the well. Recent grading just east of the school building did not uncover the well. Readings were taken around the school grounds; no methane was detected.

Artesian well No. 5 is located at 514 10th Avenue in the southwest corner of the lot. The well casing is surrounded by a 13.5-inch o.d. and 10-inch i.d. concrete cylinder which is capped with a bird bath. The well casing is approximately 7.5 inches i.d. and 8 inches o.d. and is about 6 inches above ground level. Water was trickling very slowly through a slot at the top of the casing, and along the ground from cracks in the concrete cylinder. Vegetation around the well is relatively lush. Gas bubbles were observed and the methanometer indicated the presence of methane. The gas was sampled on September 11, 1984. One pint was collected in 27 minutes; however, it was likely that some of the gas bypassed the sampling apparatus. The sample was submitted to the USGS Branch of Oil and Gas Resources Laboratory at the Federal Center in Lakewood, Colorado for analysis on September 12, 1984. The analysis indicated (Threlkeld, personal communication, 9-24-84) that the gas is biogenic methane with a small percentage of ethane. This well is plugged, most likely with cement, at a depth of about two feet from the top of the surface casing. The thickness of the plug is unknown, but gas is bubbling up around the perimeter of the plug. Mrs. Gallegos, the resident at 514 10th Avenue, had no background information on the well. Historical records indicate that this well was completed on June 16, 1886 and was drilled to a depth of 1287 feet; water was found at a depth of 1160 feet.

Artesian well No. 6 is located in the rear of the lot at 1402 7th Street. The well casing reduces from about 16 inches to 1-1/4 inch i.d. pipe from which water is slowly trickling and gas bubbles are escaping. A basin filled with water surrounds the casing and the vegetation around the basin is relatively lush. The residents of the home do not have much background information on the well but believe that the flow of water from the well varies seasonally and that gas has been escaping for at least the last six and one-half years. A rod which is inside of the 1-1/4-inch pipe is believed to be the handle of a hand-operated well pumping unit. Two one-pint samples of gas were taken from this well on August 7, 1984; one took 23 minutes, the other took 26 minutes. The sampler neck just fit inside the pipe but some gas likley bypassed the sample bottle. The samples were submitted to the USGS Branch of Oil and Gas Resources Laboratory for analysis on August 8, 1984. The analysis indicated (Threlkeld letter,

8/14/84) that gas from this well is biogenic methane with minor ethane. Historical records indicate that this well was completed on July 28, 1886 and probably drilled to a depth of greater than 1200 feet. Gas from both wells number 5 and 6 was sampled and analyzed by the Weld County Health Department. The analyses confirmed the findings of the USGS.

Artesian well No. 7 is located in the University Center lawn on a hill between the Center and 20th Street. No evidence of the well was observed. Spot checks with the methanometer indicated no methane. The University Center director, along with former University personnel and other long-time residents, were contacted for information but none was aware of the well.

Artesian well No. 8 is located under an unpaved parking lot at the northeast corner of 8th Avenue and 7th Street, the site of the old Oasis Hotel. Readings were taken at paced intervals throughout the lot and methane was not detected.

About 30 drillers' logs on file at the State Engineer's Office were reviewed in hopes of determining either the top or base of the Fox Hills Sandstone. It was determined that these logs would be of little help for that purpose.

Geophysical Logs

Various logs of oil, gas, and water wells were reviewed for this project. The types of logs are described below.

Most well logs reviewed were electric logs from oil and gas wells, on file at PI or at the COGCC, which were used to pick the tops of the Codell Sandstone and sandstones in the Pierre Shale. A typical electric log suite includes spontaneous potential, resistivity, and conductivity logs.

Cement bond logs and variable density logs for the lower part of four Bellwether Exploration Company wells drilled in June and July - Kelly 2-3, Kelly 1-3, H.I. Brown 1-27, and H.I. Brown 2-27 - in northwest Greeley were reviewed. A log of the upper 3000 feet of the Lundvall Oil and Gas Company No. 11, Gilbert 2 well in west Greeley was also reviewed. These logs were provided by the City of Greeley.

A mudlog by Balab completed on August 30, 1984 for Bellwether well Brown-Davee 1-34 was sent to us by the City of Greeley for review. To this date, this is the only mudlog we have reviewed for a well in the area of investigation. Formation hydrocarbons occur in the Parkman Sandstone, Sussex Sandstone, Shannon Sandstone, Niobrara, and Codell Sandstone. The uppermost indication of hydrocarbons occurs as a slight methane show in a silty shale at a depth of 1250 feet.

Mr. Tom Majors (personal communication, 6-27-84) described the mudlog of a gas well drilled recently near LaSalle. The log indicated gas at 60 feet (Fox Hills) and at 1100 feet.

Cased-hole (two-inch tubing) gamma, neutron, and temperature logs were run at the LaSalle water tower well by Welex. The hole was logged to a depth of 672 feet after it was determined that it would not be feasible to permit drilling to proceed any further. The gamma and neutron logs indicate the presence of a water-bearing sandstone (Fox Hills) at depths of 83 feet to 110 feet, underlain by shale and silty shale. The temperature log indicates a gradual decrease in temperature from total depth to 300 feet, decreasing more gradually to 176 feet, then decreasing sharply until gradually increasing in temperature beginning at 126 feet. The temperature log is inconclusive except to indicate that the gas entering the well is from below the Fox Hills Sandstone. A chromatograph of gas sampled in this well and analyzed by Weld County Health Department, when compared with a chromatograph of Codell gas from the Wickes #1 water well, indicated that the water tank well was emitting Codell gas.

Annulus Pressure Survey - Since the LaSalle episodes, surface casing pressures in gas wells have been monitored by the COGCC. Annulus pressure data, included in site-inspection reports dated July 13, 1984 and August 21, 1984 for wells in the Greeley area and vicinity, were submitted to us for our information on June 16, 1984 and August 22, 1984. The latter report is an update of the earlier one in that it includes data from wells not previously visited. Additional gas pressure data from a report dated April 12, 1984 were submitted to us on July 25, 1984. Pressure data from

Bellwether Exploration Company sent to the COGCC on April 20, 1984 were submitted to us by the City of Greeley on June 7, 1984.

Three categories of surface casing annulus gas pressure are indicated on Plate 8. The categories are 0-50 psi, 51-100 psi, and greater than 100 psi. The map illustrates the occurrence of high annulus pressure in a well regardless of when the well was checked or whether the well has subsequently been bled off or squeeze cemented. Data used in preparing this map are from the COGCC.

On a large scale, throughout the project area, gas well high-pressure patterns have not been established, although a higher number of high-pressure readings occurred south and east of LaSalle and northwest of Greeley. It is understood that monitoring of the wells will be a continuing project for the COGCC.

Gas Chemistry - Gas samples were taken from artesion wells No. 5 and No. 6 in order to determine the nature and source of the gas. Gas from each sample was analyzed by the United States Geological Survey for component percent of mixture using gas chromatography and the degree of stable carbon isotope enrichment of the methane fraction using a mass spectrometer. The USGS had made similar analyses of gases in the LaSalle area (Rice, et al. 1984).

The chromatographs of these gases indicate that the air-free samples contain a high percentage of methane, a very low percentage of ethane, and no heavier hydrocarbons (propane, butane, pentane, etc.). The mass spectrometer analysis of the methane carbon indicates that the gases are rich in the light isotope ^{12}C. These data indicate that the gases are "light and dry" and are biogenic in origin (see Table 2). Analyses of samples from the wells by the Weld County Health Department confirm this conclusion.

Rice, et al., (1984) summarize the origin and characteristics of biogenic and thermogenic gases. Biogenic gases are generated at shallow depths and

TABLE 2

ANALYSES OF GAS

ARTESIAN WELLS NO. 5 AND NO. 6

Well	Carbon Isotope Ratio (ppt)	$\frac{C_1}{C_{1-5}}$	Air	C_1	CO_2	C_2	C_{3+}	
Artesian			29.1	70.65	0.15	0.10	0	Tot. Gas
Well	-67.09	.9986	-	-	-	-	-	
#5			-	99.65	0.21	0.14	0	Air-Free
Artesian			31.77	67.83	0.18	0.22	0	Tot. Gas
Well	-67.26	.9968	-	-	-	-	-	
#6			-	99.41	0.27	0.32	0	Air-Free

CO_2 = Carbon Dioxide

C_1 = Methane

C_2 = Ethane

C_{3+} = Propane, Butane, & Pentane

Analyses performed by U.S. Geological Survey, Office of Energy and Marine Geology, Branch of Oil and Gas Resources

low temperatures by the decomposition of organic matter by microorganisms in environments free of dissolved oxygen and sulfate. In contrast, thermogenic gases are "heavy and wet" and are formed by the thermal degradation and cracking of kerogen, oil, and other non-hydrocarbon precursors with increasing temperature and geologic time. Methane in thermogenic gases is accompanied by heavier hydrocarbons and is isotopically heavier than biogenic gas (carbon isotope ratios generally heavier than -50 ppt). Most gas produced from commercial oil and gas fields is thermogenic.

There is no evidence of subsurface migration of gases from commercial producing formations and(or) gas wells to artesian wells No. 5 and No. 6. Such migration would be evident by heavier isotope enrichment and the occurrence of heavier hydrocarbons, along with methane. Figure 4 illustrates that the Fox Hills gas and that found in wells Nos. 5 and 6 are not exactly the same gas, but that both are biogenic.

The source of the biogenic gas escaping from these wells has not been determined. The artesian well gases are slightly heavier and wetter than gases analyzed from Laramie-Fox Hills water wells by Rice and Threlkeld (1982). It is conceivable that biogenic gas could be produced in or near the 1100-foot Sandstone. It is reasonable to assume that the source of the biogenic gas is from a source deeper than the Laramie-Fox Hills aquifer. The gas could be coming from the 1100-foot Sandstone or from any zone above it and below the Fox Hills.

Analyses of gas sampled from six vent sites in the vicinity of the Wickes Lumber Company in LaSalle indicate that the gas is thermogenic in origin and migrated from deeper, thermally mature rocks (Rice, et al., 1984). These vent gases are almost identical chemically and in isotopic composition with Codell gas produced nearby. In addition, the gas sampled from the water well beneath the old LaSalle water tower was "heavy and wet", indicating thermogenic (Codell) gas.

Water Chemistry

Water samples from artesian wells Nos. 5 and 6 were collected and analyzed

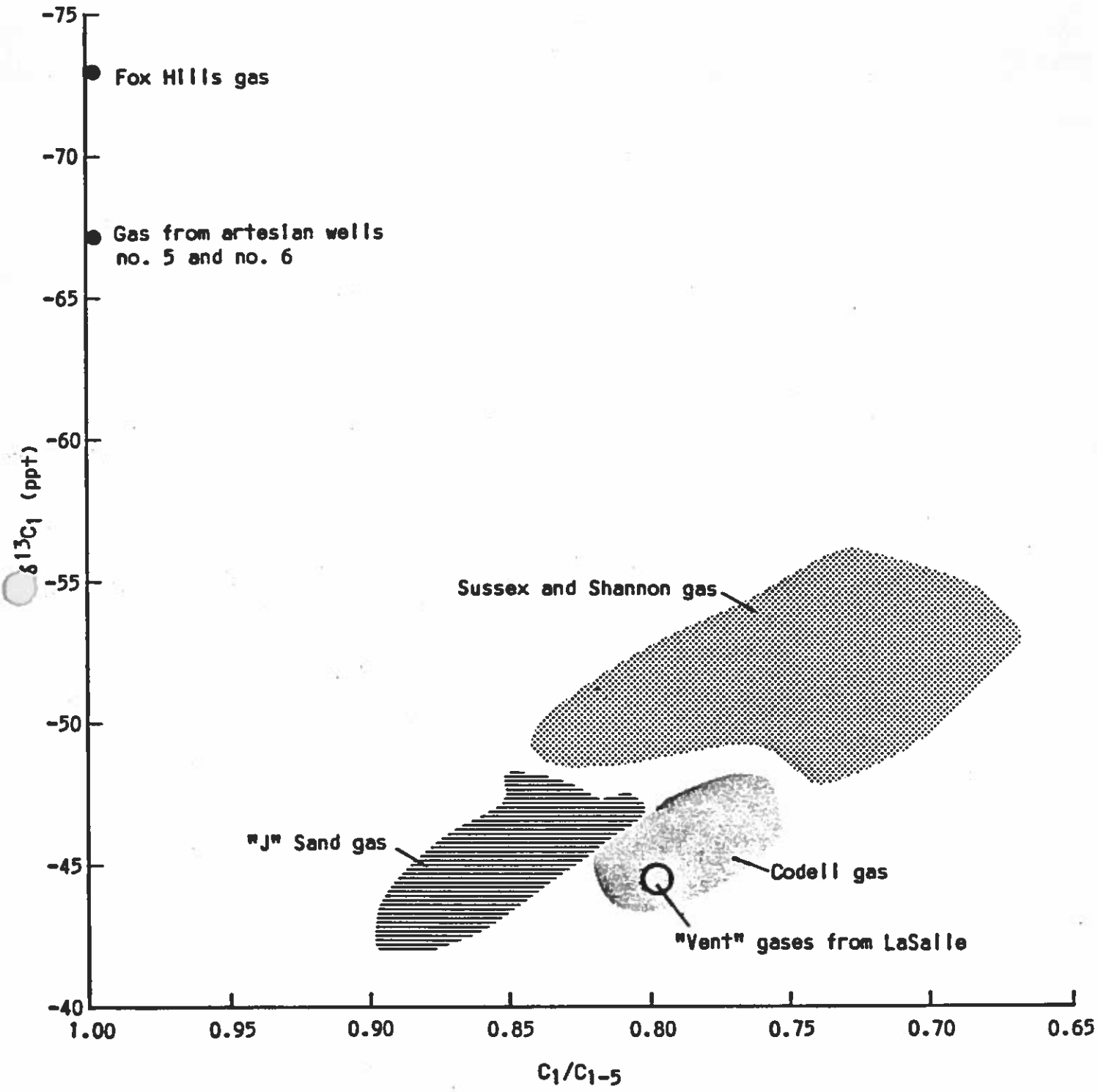


Figure 4 Modified after Rice et. al., 1984. Hydrocarbon composition versus methane carbon isotope ratio of natural gas from Wattenberg area, Denver Basin, showing relationship of Fox Hills methane and methane from artesian wells no. 5 and no. 6.

by the Weld County Health Department. Those analyses and an analysis of a typical Fox Hills aquifer water are shown on Table 3. It can be seen that the water from the flowing wells is significantly higher in sodium and in dissolved solids than what would be expected from the Fox Hills.

LaSalle Model

At the beginning of this project, it had been planned that the geological report on the LaSalle event would serve as a model for the Greeley study. The report on LaSalle is in preparation now (John Rold, personal communication). Although the "model" is not available in written form, John Rold, Director, Colorado Geological Survey, has generously shared information and ideas on the events at LaSalle, and how the experience there may be of value in the Greeley investigation. The following sequence of events at LaSalle was developed largely from conversations with Mr. Rold.

Development of Problem - On the evening of February 9, 1984 an explosion was heard and a jolt was felt about two blocks from the Wickes lumber yard. People were variously concerned that it was caused by an earthquake, a gas line leak, a sonic boom, or some other possible hazard. The local police and fire departments were alerted and the fire marshall spent the rest of the night looking for the location of the event site, but without success.

On February 10th, an employee of the Wickes Lumber Company noticed that the blacktop in the lumber yard had buckled and gas was hissing through cracks in it. A backhoe was brought in and at a depth of three to four feet a four-inch well casing was found. When uncovered, the well (designated Wickes #1) was bubbling water and gas. The well was not measured for depth, but Halliburton was called in by the Town of LaSalle to plug it with cement. This consisted of dumping 104 sacks of cement, which should fill 1100 feet of four-inch casing. While the cement was being poured, gas continued to bubble up through it while the cement was setting up.

A workover rig was called in after it was decided that a pressure problem existed. The workover rig drilled 225 feet in cement and at 68 feet went from a foamy cement to a hard, dense cement. Fifty sacks of cement were

Table 3

ANALYSES OF WATER, ARTESIAN WELL NOS. 5 AND 6
(Reported 9/28/84 by Wes Potter,
Weld County Health Department)

	No. 5 10th Ave	No. 6 7th St	Typical Fox Hills
Turbidity	0.95	0.53	
F	3.3	3.3	1.7
$NO_{3/N}$	nil	nil	nil
pH	8.2	8.2	8.3
Hardness	12.0	16.0	15.0
$CaCO_3$	11.0	12.0	11.0
Mg	<1	1.0	1.0
Na	440	445	260
Cl	400	420	
SO_4	0	0	0
Alkalinity as $CaCO_3$	430	420	460
TDS	1120	1130	600
NH_3 as N	1.1	1.0	
K	2.4	2.2	

Values in milligrams/liter

then pumped into the hole and it was squeezed at 300 psi pressure while the cement set up. A pressure gage had been placed before the cement was pumped in. Within an hour gas pressure had risen to 100 psi, an abnormally high pressure. By 5:30 p.m. on Friday, February 17, it was thought that the problem had been solved. At 2:00 a.m. on Saturday the 18th an explosion occurred in the lumber yard which was subsequently destroyed by fire.

The Wickes #1 well was redrilled to 386 feet and a casing detector was run. It was determined that the casing was in poor condition down to 68 feet, its total length. A thermal decay time (TDT) log showed that surface gravels were gassy, and that the Fox Hills had gas in it.

Investigation - Early in the LaSalle investigation, three sources of the gas which caused the explosion were postulated:

1) Gas in the Fox Hills had leaked to the surface.
2) A Greeley Pipeline Company gas line had ruptured.
3) A cement squeeze job on a well being hydraulically fractured 0.75 mile south of town forced gas to the surface in Greeley. LaSalle

Volunteers scoured the town in an effort to identify additional well locations (water and oil/gas); about 200 wells were located. A program of backhoe excavating was undertaken in the most critical locations in an attempt to find wells making gas. When it became obvious that the backhoe work was too time consuming, costly, and destructive of the surface, an auger rig was brought in and vent holes were drilled and cased. The holes were drilled to about 10 feet, and cased with four-inch PVC pipe, perforated in the lower four feet and seated in the hole. A 10-foot section of pipe was attached so that gas was vented above the level at which casual ignition (by cigarettes, matches, etc.) might occur. When these vents were first installed, there was sufficient gas for most of them to be flared, but burning was not sustained because of insufficient gas pressure and gusting wind. The vents were checked periodically with methanometers. Gas from the Wickes #1 and several vent wells was sampled and analyzed (Rice, 1984). Both the composition of the gas and the degree of stable carbon isotopes indicated that the gas was from the Codell Sandstone which is being developed in the vicinity. The area of greatest concentration of

combustible gas measured by the methanometers was within the Wickes Lumber Company sales yard where consistent reading of 80 percent combustible gas were measured.

When the relatively high concentration of gas was found in the Wickes lumber yard, it was suspected that there could be another well in or near the area. Aerial photographs taken in 1930 showed a small shed (possibly a well house) where a well (later designated Wickes #2) was found after the concrete and asphalt were dug up in and near the basement where the explosion had occurred. The Wickes #1 and #2 were allowed to blow gas and water.

About two weeks after the explosion in the Wickes #2 well, buckling and cracks in the asphalt in the United Bank parking lot developed. A pit was dug about three feet deep which uncovered a casing flowing gas and Fox Hills water. A rig was set up over the hole and after drilling through some backfill(?) gravel, they drilled up a pump rod and a pump. The foundation engineer (Carl Hauser, Loveland) remembered a well beneath the foundation on the west side of the bank. A backhoe pit was dug down to 16 feet beside the drive-up window and encountered no gas or water. An excavation was dug under the bank foundation where the plans showed a well location, and casing was found. Engineers were called in from Oklahoma City to install a high pressure tap. When they tapped the casing, there was a brief hiss and nothing more.

John Rold worked primarily with logs and other data from about 50 oil/gas wells in an area of about 25 square miles, centered on the town of LaSalle. He worked with only about three wells (at Wickes) which probably were water wells. Beds that he used as markers are the 800-foot bed, the 1100-foot bed, the Sussex, and the Codell.

Rold found a large number of small faults (three to five per well) in examining the geophysical logs. Most faults had 10 feet to 20 feet of displacement but a few had over 100 feet. In only one instance was he able to determine with confidence that one of these faults was found in more than

one well; that fault was traced in only two wells. Rold feels that these faults were formed by a series of landslides which occurred during deposition of the shales while they were below the original sea water. His plot of the amount of displacement against depth indicated that the faults die out upward. The presence of a large number of faults in the section could provide additional avenues of travel for gas trapped in any reservoir, whether it is Codell or some higher unit.

On the morning of June 17, 1984, a second important event occurred in LaSalle. An off-duty fireman noted that a small section of sodded ground beneath the town water tower had become marshy and gas was bubbling through the water-soaked sod. This was brought to the attention of Town officials and excavating equipment was mobilized to determine the nature of this occurrence.

A well was uncovered in an old buried concrete structure. By the time the soil and debris had been removed from the basement, the level of water in the well had subsided to about 8 to 10 feet below the ground surface; however, a distinct bubbling sound could be heard as gas escaped the water in the well. The drilling history of this well was recorded in minutes of the Town Board of Trustees, February 16, 1917.

The Town contracted to have the newly discovered well cleaned out by redrilling to the total depth reported in the Board of Trustees' records. The records show that drilling was authorized for as much as 1100 feet, but it appears possible from reading these documents that the well may only have been drilled to 950 feet.

Thomas B. Majors, Petroleum Consultant, hired by the Town of LaSalle, indicated (personal communication, 6-27-84) that two days before the June 17th event, the Unioil #1 Ewing, about 0.6 mile northeast of the water tank, had experienced a pressure buildup. The pressure was bled down and the well was being monitored, but Majors could offer no opinion as to any effect on the LaSalle water tank well when pressure was reduced in the Unioil well.

Chief Carl Harvey of the LaSalle Police Department, whose personnel have been monitoring the various vents in the town, reports that from late March to mid-June, a decline was found in gas from all venting wells. On June 18, a marked increase was found. The Unioil well was killed early in July and squeezed on July 10. By late July, the wells in town were venting approximately at the level which obtained before the water tank well discovery. The monitoring continues and is finding low levels of gas from Wickes #1, the water tank well, and United Bank #1. No gas is now found in Fox Hills water wells or the alluvium.

Drilling and cleanup continued at the water tank well until it reached 680 feet, at which point no progress was being made. It was decided to terminate drilling and log the hole. The Weld County Health Department made chromatographic analyses on a sample of gas taken from the water tank well. A previous gas sample analyzed from the Wickes #1 had been determined to be Codell gas. The water-tank gas sample run by the Health Department matched almost exactly the Wickes analysis, indicating that it too was producing Codell gas.

Oil and Gas Well Completion Practices

While all oil and gas wells are not constructed exactly alike, certain procedures are typical in the area. The surface hole is normally drilled with a diameter of 12-1/2 inches or 13-3/8 inches to 50 feet below the Fox Hills aquifer, and a surface casing of 8-5/8 or 9-5/8 inches is cemented into the bore. After the cement has set, the drilling is resumed with about an 8-inch diameter bit to about 100 feet below the producing formation.

Production casing, about five inches in diameter, is then lowered to the bottom of the hole. Cement is forced up from the bottom into the annulus between the production casing and the formation. Present regulations require that the casing be cemented at least 300 feet above the base of the Niobrara Formation. The production casing and cement are then perforated in the producing zone and the formation is hydraulically fractured.

COGCC regulations for about 15 townships including the Greeley area now require that the annulus between the production casing and the formation be cemented to a depth of about 3000 feet. This is intended to seal all the possible aquifers in the area, to prevent any gas which might escape through the production zone cement from rising to the higher sands, and to act as a seal in the event of production casing failure.

A production tubing commonly about 2-1/2 inches in diameter is then placed in the casing with a packer just above the producing zone. Thus gas is conveyed through the inner tubing to the surface. Ideally, no production gas will be in either the tubing-casing annulus or in the casing-formation annulus.

IV. DATA ANALYSIS

Regional Geology

The area of this investigation is situated in the Denver basin, a part of the much larger Denver-Julesburg (D-J) structural basin. The D-J basin is a broad asymmetrical structural depression that extends from southern Colorado northward into southeastern Wyoming. In an east-west direction, the basin extends from western Nebraska and western Kansas to the Front Range. The strata on the western flank of the basin, which end abruptly along the mountain front, dip steeply to the east and the strata on the eastern flank of the basin dip gently to the west. The deepest part of the basin is on the west near the Front Range.

The city of Greeley, which is situated along the axis of the Denver basin, is underlain by thousands of feet of sedimentary rocks of Cretaceous age. Beneath these strata are older Precambrian basement rocks. Many of the Cretaceous sedimentary rocks are important sources and reservoirs for hydrocarbons and have been tested for petroleum development potential. It is estimated that the thickness of the Cretaceous section is greater than 8000 feet in the project area.

Oil and gas fields within and adjacent to the project area are shown on Figure 5. Production is primarily, in ascending order, from the D and J Sandstones of the Dakota Group, the Codell Sandstone, the Niobrara Formation, and the Shannon and Sussex Sandstones of the Pierre Shale.

Stratigraphy

The Laramie Formation and the Fox Hills Sandstone, which crop out in the project area, overlie as much as 7000 feet of Pierre Shale, a dense, fossiliferous, silty, marine shale. Included in the Pierre Shale are five sandstones or sandstone intervals that are continuous throughout the project area. These sandstones are from youngest to oldest: "1100-foot", Richards, Parkman, Sussex, and Shannon. The Pierre Shale also contains other discontinuous or lenticular sandstones throughout the section. Underlying

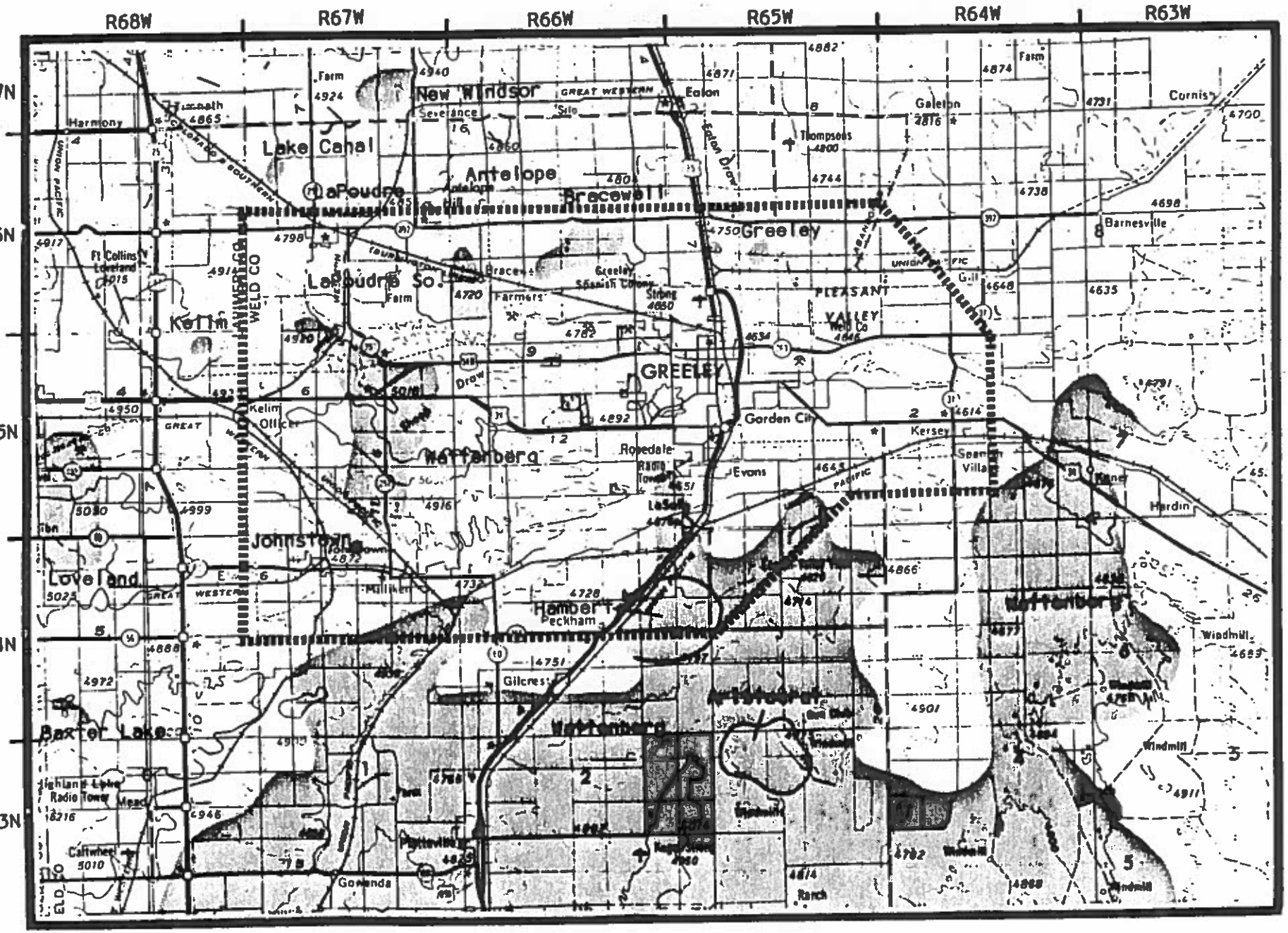


Figure 5 Generalized oil and gas field location map; from Scanlon, 1983

scale 1"=3.95 miles

the Pierre Shale are the calcareous shales and limestones of the Niobrara Formation. The Codell Sandstone is immediately below the Niobrara. The Niobrara and Codell are mapped together in some portions of the area of investigation.

Typical depths of sandstone tops are as follows: 1100-foot - 1100 feet, Richards - 2500 feet, Parkman - 3600 feet, Sussex - 4400 feet, Shannon - 4800 feet and Codell - 7100 feet (see Figure 2). All of the sandstones are continuous throughout the project area, although the Shannon appears to be less sandy in the eastern third of the study area and the Sussex appears less sandy in the western quarter of the project area.

Geologic Structure

Structure contour maps showing the top of the Codell, Shannon, Sussex, Parkman, Richards, and the 1100-foot Sandstones were prepared to illustrate the structure of the units. The structure contour maps were also used to determine which sandstones were penetrated by deep water wells. All of these maps use mean sea level (msl) as the reference elevations.

The structure contour maps represent the tops of the sandstone or the tops of the sandstone intervals. This provides a consistent data base for each map. For example, the lenticularity of sandstones within the Shannon and Sussex intervals would provide an inconsistent datum for contouring if tops for each sand were used instead of the interval tops.

Codell Map (Plate 7) - The Codell Sandstone was the lowermost sandstone contoured for this project. The elevation of the top of the Codell ranges from -2150 feet to -2550 feet. The lowest elevations are between Greeley and a large normal fault in the western part of the project area. The general strike of the Codell is north-south in the eastern half of the project area and generally northeast in the western part. Dips are low, ranging from less than one degree to about three degrees.

The large northeastward-trending fault in the western part of the project area is believed to be related to one mapped in the "J" Sandstone (Pruit and

Coffin, 1978). The upthrown side of the fault in the Codell is to the northwest. The displacement is less than 50 feet at the north and about 300 feet at the south. A minor fault extends southwest from this one. It is believed that the main fault dies out in the overlying Pierre Shale and does not displace sandstones above it. Two minor faults are also mapped northwest of Greeley.

A structure contour map of a Codell prospect area north of Greeley was provided by Bellwether Exploration Company and used with their permission along with our data. The minor faults northwest of Greeley are from Bellwether's map.

A synclinal zone, probably representing the axis of the Denver basin, trends northeastward beneath the city of Greeley. The apparent deepest part of this axis is beneath the western part of the city. East of town, several subparallel anticlinal and synclinal features trend and plunge westward toward the main synclinal axis. West of the city, anticlinal and synclinal features trend and plunge in a variety of directions on either side of the major fault.

Shannon (Hygiene) Map (Plate 6) - The elevation of the top of the Shannon ranges from -100 feet beneath Greeley to 450 feet on the west. The elevation rises to -50 feet on the east side of the study area.

The most notable structural feature is the northeastward-trending steepening of dip west of Greeley. This steepening overlies the major fault mapped at the Codell level and probably is a reflection of that structure.

A fault trending roughly east-west, with a displacement of less than 50 feet, was mapped in the southwestern part of the project area between Johnstown and Milliken.

At the Shannon level, the trend and plunge of anticlinal and synclinal features are generally to the east and northeast. The main axis of the Denver basin at this level trends approximately north-south beneath Greeley, but could not be defined precisely with the control available.

Sussex (Terry) Map (Plate 5) - The elevation of the top of the Sussex ranges from about 350 feet, north of Greeley, to over 900 feet at the western part of the project area. The elevation rises to over 400 feet at the eastern study boundary. A synclinal feature, reflecting the axis of the Denver basin at the Sussex level, trends north-south beneath the city.

A steepening of the dip similar to that found in the underlying Shannon Sandstone occurs in approximately the same location at the Sussex level, and is approximately coincidental with the fault in the Codell.

Parkman (Larimer-Rocky Ridge) Map (Plate 4) - The elevation of the top of the Parkman ranges from less than 1050 feet to greater than 1550 feet, and gradually rises to the west. A structural low trends north-south through the area beneath Greeley.

The steepening of dip noticed in the Shannon and Sussex Sandstones covering the Codell fault is less pronounced in the Parkman. The steepening is not as marked and is less well defined than in the lower units. This lack of definition indicates that the effects of the fault are diminishing toward the surface. The axis of the Denver basin follows a curved trend from north-north-westward to northward beneath Greeley.

An east-west trending fault, about three miles in length, with a displacement of about 50 feet, was mapped in the vicinity of Johnstown and Milliken, southwest of Greeley. Another minor fault, less than a mile in length, was mapped northwest of Greeley.

Richards (Greeley) Map (Plate 3) - The elevation at the top of the Richards ranges from less than 2000 feet to greater than 2700 feet. The Richards is nearly flat-lying in the eastern half of the project area where elevations are lowest. Elevations gradually rise westward.

The steepening of dip in lower sandstone units which correlates with the fault in the Codell is only noticeable in a small area north about one mile from a line between Johnstown and Milliken. North and south from this area

the contours are irregular, indicating an almost complete lack of correlation with structure in the lower units. The axis of the Denver basin essentially has a northwestward trend through Greeley; however, this axis is less well defined in the Richards than it is in any of the lower units.

1100-foot Sandstone Map (Plate 2) - Elevations in the 1100-foot Sandstone range from less than 3500 feet in the east to greater than 4100 feet in the west. This sandstone is nearly flat-lying in the eastern half of the project area and gradually rises westward.

In the 1100-foot Sandstone, only a slight vestige of the steepened dip in the lower units remains. Without maps of the lower sandstones, little significance would be placed on the change in dip. Hence, at this level there is no suggestion of the fault mapped in the Codell.

The axis of the Denver basin is not defined at this mapping horizon. Two structurally low areas trend east-west, north and northeast of Greeley, approximately at right angles to the axis as mapped in the lower units.

A prominent anticlinal fold trending northeastward about one mile east of LaSalle trends toward the large structurally low area northeast of Greeley.

In summary, the study area is situated along the easternmost portion of the western flank of the Denver basin, approximately straddling the basin axis. This is indicated in the mapping horizons which gradually rise in elevation from east to west in the study area, with a structurally low area underlying Greeley. In the lowest three mapping horizons, the trend of the axis is well defined, but in the upper three horizons, it is increasingly less well defined until in the 1100-foot Sandstone it is not apparent.

The northeastward-trending fault mapped in the Codell appears to die out upward before it reaches the Shannon Sandstone and younger sandstone beds. Almost coincident with this fault is a steepening of dip in the overlying Shannon, Sussex, and Parkman Sandstones. This fold is increasingly more gentle and less prominent toward the surface and it is not apparent in the

Richards and the 1100-foot Sandstones. In the lower sandstones, this fold is an expression of the underlying Codell fault. The fault may be a deep structure with growth fault characteristics. Typically, in growth faults, displacement increases with depth and sediment thickness increases on the downthrown side. Perhaps a more detailed study of well logs in this questionable area would reveal the presence of a major fault throughout the section. Such a study would most likely reveal shallow growth faults, as those in the Pierre Shale, throughout the area investigated.

Cross-sections A-A' and B-B', prepared through the study area, and cross-sections C-C', D-D', E-E', and F-F', prepared across the northwestward-trending fold in the western part of the project area illustrate structure and stratigraphy. The cross-sections are included on Plates 9 and 10.

Water Wells

The deep (500 feet+) domestic water wells visited in the field do not penetrate the 1100-foot Sandstone. Methane gas was not detected in these wells, although biogenic methane gas escaping from the Laramie-Fox Hills aquifer is not uncommon in Weld County.

The eight wells drilled in Greeley in the 1880s penetrated the 1100-foot Sandstone which produced artesian water. Biogenic methane gas was detected bubbling from wells No. 5 and No. 6. The other six wells are apparently buried beneath soil cover and(or) concrete pavement.

LaSalle Model Conclusions by Rold

Rold surmised that gas pressure in the Wickes #1 entered that well from the Fox Hills, as indicated by the fact that gas bubbled through only the upper 68 feet to 70 feet of cement while the hole was being plugged. After the plug was placed in the Wickes #1 under pressure, gas was then forced laterally in the Fox Hills to the Wickes #2 which was the closest probable point of pressure release. This gas was identified definitely as being from the Codell, by carbon isotope methods (Rice, et al., 1984) and by chromatographic analysis.

In his examination of oil well geophysical logs, Rold reached the conclusion that numerous faults which he found in the Pierre Shale were formed in submarine landslides on an eastward-sloping shelf. The displacements on these faults ranged from about 10 feet to over 100 feet, but the faults are limited to local areas. Only in two instances were the same faults found to occur in adjacent wells. Based on the presence of these faults, Rold postulated that gas from the Codell Sandstone migrated upward along fractures in the shale and may have been temporarily stored in underpressured sandstones. The gas then moved upward, either directly or from temporary reservoirs, along other fractures, along poorly cemented well casings, or through abandoned water wells to the Fox Hills Sandstone.

In summary, Rold indicated that the critical geologic factors contributing to the event at LaSalle were:

1. The Wickes #1 well probably was drilled into the 1100-foot Sandstone, although he is not absolutely certain of this.
2. Gas migrated up this well from the sandstone and built up a pressure against the cap of overlying frozen ground and asphalt.
3. The pressure buildup was large enough to force the gas through the Fox Hills into the Wickes well where the casing was in poor condition.

Possible Leakage Mechanisms at LaSalle

In order to discuss the potential effects of gas leakage to the surface, or near the surface, the two types of explosive methane gas known to occur in the area should be discussed. Biogenic gas is formed at shallow depths and low temperatures in environments free of dissolved oxygen and sulfate. Thermogenic gas is formed by "...thermal degradation and cracking of kerogen, oil, and other nonhydrocarbon precursors..." in an environment of increasing temperature in geologically older rocks (Rice, et al., 1984). Generally it would be unlikely for biogenic gas to form any deeper than about 1000-2000 feet. Thermogenic gas would form below that depth. In terms of hazard potential, it makes no difference whether methane gas is biogenic or thermogenic if it occurs in the right concentration for an explosion.

The presence of Codell gas at the surface in the LaSalle area could be the result of one, or a combination, of the following mechanisms:

1. Penetration of gas from the Codell Sandstone upward through fractures to the Fox Hills Sandstone and to the overlying alluvial gravels.
2. Leakage of gas from oil/gas wells which have been inadequately cemented, thus allowing passage to higher reservoir rocks.
3. Leakage from wells with ruptured casing.

The first of these possibilities seems to be the least likely if fracture porosity is assumed to have developed as a result of landslide-induced faulting during consolidation of the Pierre Shale. These faults probably would heal in the massive shale sections within which they occur unless there was sufficient gas pressure to maintain them in a more permeable or open state. Another possible path of migration through fracture porosity would be along a tectonic fault. Tectonic faults are caused by structural forces in the earth's crust, rather than by settlement and reduced strength induced by superincumbent load and increased pore pressure which usually are mechanisms active in the development of landslides.

If this natural mechanism were the case, it would probably follow that hydraulic fracturing of the Codell to stimulate gas production would intercept natural fractures in the overlying shales. Those natural fractures in turn must intercept other fracture sets or a sandstone bed to transmit the gas either laterally or vertically.

No tectonic faults have been found that would act as conduits in the LaSalle area, leaving the "growth faults" noted by Rold as the other possibility. The fact the these faults do not cut sandstones would imply that vertical migration into or from an upper sandstone would require some other conduit such as a bore hole or a tectonic fault. Initiation of leakage from the Codell through hydraulic fracturing is implied since such action is necessary to move gas from the Codell into wells. Without such measures, gas cannot be produced from the Codell because of the very low natural

permeability of the formation. In our opinion, the probability of gas escape from the Codell in the manner described above is low.

The second two possibilities have much in common. In each, the gas produced from the Codell would be released under significant pressure to the hole outside the production casing. Since the hole is normally open to the formations in the Pierre Shale section, the gas would be free to penetrate any under-pressured sandstones in the section. Gas could then move laterally until the sandstone was cut by another well, whether it be a water well or another oil or gas well. If the sandstone was intercepted by an oil or gas well, a buildup of annulus pressure in that well would result. If by a water well, the gas would be vented to the surface. This appears to be a more likely mechanism.

Greeley Analog

Greeley has no direct analog for the LaSalle model, although the geologic environemnt, oil and gas development, and presence of aquifers are similar in both areas. According to newspaper reports of the early to mid-1880s, artesian water wells have been drilled to the 1100-foot Sandstone in Greeley. A list (Table 1) of eight artesian water wells was provided by City officials for this investigation. A review of the location descriptions on the ground has enabled us to find wells No. 5 (10th Avenue) and No. 6 (7th Street) and tentatively, No. 1 (Lincoln Park). The latter well was reported by park personnel to be buried under the concrete pad at the base of the fountain. At this writing, we have analyses of gas and water from wells No. 5 and No. 6, but the origins of both are still unknown.

Water and gas flow from these wells, which are just above ground level. The precise depths of the wells and how they were constructed are not known, although newspaper accounts indicate that both were drilled to depths greater than 1200 feet. The aquifer supplying water to the wells may be the 1100-foot Sandstone or the 800-foot Sandstone, if the latter is present in the area. Based on analyses of water from both wells (Table 3) and based on the piezometric head, the water is not from the Fox Hills Sandstone.

The gas flow in both wells is biogenic (Threlkeld, letter 8-14-84 and personal communication 9-24-84; and Potter, personal communication 9-28-84), but contains some ethane which is absent in gas from the Fox Hills, and which indicates a deeper origin than gas from that formation. This gas probably comes from one of the Pierre Shale sandstones which is within the generally accepted maximum depth (about 1000 feet to 2000 feet) for the formation of biogenic gas.

In their present condition, the wells cannot be probed to determine total depths and the depth or depths of the water and gas inflow. Since the 800-foot Sandstone was not found to be a laterally persistent rock unit, the most likely aquifer which this well encountered was the 1100-foot Sandstone. The gas is under low, but steady pressure judging from the manner in which it escapes, and it probably comes from the 1100-foot Sandstone.

Until more specific information on the depth and construction of these wells is available, we can only be certain that they produce biogenic methane gas. The water analyses and the slight piezometric head indicate that the water is not from the Fox Hills.

V. EXISTING PROBLEMS DEFINED

There are several problems for which no evidence, or only indirect evidence, has been found and for which answers are needed. Although in the LaSalle area indirect evidence points toward the 1100-foot Sandstone as a temporary reservoir and as a probable migration zone of Codell gas in the upper rock section, the physical characteristics of this sandstone are unknown. In the Greeley area, two flowing water wells which produce biogenic methane are probably, though not certainly, deriving water from the 1100-foot Sandstone. The mechanism(s) by which Codell gas would migrate to the 1100-foot Sandstone are at this writing speculative. Associated problems are:

- The mechanism through which gas migrates from the Codell Sandstone to the surface in the LaSalle area. Only indirect evidence and professional judgment are now available to answer this problem.

- Point of entry of the gas in the LaSalle wells. This gas is from the Codell, as concluded from its composition; however, where it enters the wells is not known. The point of gas entry into Wickes #1, Wickes #2, United Bank #1, and the various vents in LaSalle was apparently at the base of the gravel or in the Fox Hills just below the gravel. This observation implies a vertical conduit other than Wickes #1 since this well had been plugged with cement. Possible explanations are that the gas came from the water tank well, through faulting, or through an undiscovered well.

- Source of the gas and the water from the 10th Avenue (No. 5) and 7th Street (No. 6) wells in Greeley. While the gas is definitely not from the Codell, and it is wetter and heavier than Fox Hills gas, the source has not yet been established. Likewise, the water in these wells is not from the Fox Hills Sandstone, but we have no direct examples of 1100-foot water characteristics with which to compare it.

- The anomalous annulus pressures in some petroleum wells. In some wells, these pressures have been shown to be the result of problems within the well; the reason(s) for others is not apparent, but the pressure could result from migration of gas from another well or wells.

- The relationship between the water tank well in LaSalle, and the Unioil #2 Ewing well about 0.6 mile to the northeast. An anomalous pressure was noted in the Unioil well two days before the surface manifestations of the water tank well were observed.

- The relationship between the water tank well and the Wickes #1 and #2 and United Bank wells. The park area around the base of the water tank had been checked for methane during the LaSalle investigations and none was found.

- The relationship between the Mineral Resources Dabco #2 well which was fractured with carbon dioxide, and the LaSalle vents in which the gas, while Codell in hydrocarbon characteristics, was somewhat higher in carbon dioxide than other Codell samples. This could indicate a direct connection between fracturing the oil well which contained carbon dioxide in its annulus, and the venting at LaSalle.

VI. CONCLUSIONS

The conclusions reached in this report are largely based upon deductions and inferences using indirect evidence. Other investigations by State agencies are in progress, but have not been completed. The work of these agencies has been shared freely with us during this investigation; however, it is possible that the final reports on their studies will take into account information not available to our investigation. In view of this situation, it may develop that some of the following conclusions could be modified, and possibly eliminated.

Safety Problems in Greeley

No problem exists in the Greeley metropolitan area at this time if:

1. The two artesian wells (Nos. 5 and 6) now producing biogenic methane are left open and are not contained or enclosed in a manner that would allow explosive mixtures of gas to accumulate. These wells would best be allowed to continue to vent gas as pressure relief wells.

2. The other six artesian wells (Nos. 1-4, 7, and 8) do not manifest themselves as gas-producing wells.

Potential Future Problems in Greeley - The fact that the deep artesian wells were drilled about 100 years ago and have not caused known problems to date is an indication that they may be effectively benign. But depending upon the circumstances, these wells could pose a problem. There is no simple, economical way of determining the exact locations of these wells and they could make themselves known if the rock unit(s) into which they were drilled become overpressured, from whatever causes, with gas or water. Sufficient pressure relief (water and gas) may have been provided in the past by artesian wells Nos. 5 and 6. The only cause for concern is that external conditions might adversely affect the known, but unlocated wells, and cause them to manifest themselves in the future. Such reaction might be from improper completion of oil and gas wells and(or) from plugging wells Nos. 5 and 6. This possibility should be mitigated by adherence to State and City

rules, orders, and regulations relating to oil and gas wells, and by ensuring that wells No. 5 and 6 are not plugged.

Another potential mechanism by which problems could arise in Greeley is the possibility that Codell gas, which is assumed to be present in the 1100-foot Sandstone in the LaSalle area, could migrate northward and northeastward to the Greeley area. This is an unlikely possibility since the geologic structure indicates that the 1100-foot Sandstone is structurally low beneath most of the city. Thus, any Codell gas in the 1100-foot Sandstone in the LaSalle area would be likely to migrate southwestward and westward, away from Greeley. There is the possibility that Codell gas, if introduced into the 1100-foot Sandstone north of Greeley, could migrate updip into the area where the artesian water wells were drilled. The element of uncertainty is that we do not have direct evidence that these wells penetrate the sandstone, we do not have precise structural information on the depth of the 1100-foot Sandstone in the Greeley area, and we have no knowledge of areal variations in permeability in the 1100-foot Sandstone.

A second potential problem in the area is that water well drillers might encounter high-pressure gas pockets in the 1100-foot Sandstone. Water well drill rigs do not normally include blow-out prevention gear in their equipment. Use of this gear conceivably could mitigate a problem of explosion and fire.

Potential Problems in the Area of Investigation Outside of the City of Greeley - (The problems at LaSalle are well known; reference to them is excluded here.) The smaller towns in the area of investigation could be subject to potential problems if gas migration should occur in the 1100-foot Sandstone into water wells which penetrate the sandstone. Gas availability could be the result of porosity caused by tectonic faulting in the western part of the area, or it could be a result of leakage from oil and gas wells into the 1100-foot Sandstone. Leakage would be more likely from wells drilled before COGCC Order No. A-1-1 went into effect on May 30, 1984, than it would be from wells completed in compliance with that order.

Greeley Oil and Gas Wells

As of this writing (9-28-84), over 40 oil and gas wells have been drilled within area enclosed by the the Greeley city limits (see Table 4). Of these, nine wells were inherited with the latest annexations and 14 are not in the city and are therefore not subject to City regulation. The inherited wells were completed before the existing COGCC order and the City of Greeley regulations went into effect. For this reason, it is more important to monitor pressures on those 23 wells than on the others. There should be no problems with oil and gas wells drilled in the future, providing existing orders and regulations are followed and the procedures are properly carried out.

Greeley Water Wells

Eight deep artesian wells were drilled about 100 years ago. The precise locations of only two of these wells (No. 5 and 6) have been noted, and only the general locations of the others are known.

Both water and gas are being produced at the surface in wells No. 5 and 6. The water and gas are both probably from the 1100-foot Sandstone. Neither the water nor the gas is from the Fox Hills Sandstone. The gas is biogenic; hence, its source is not in the Codell Sandstone.

No danger should occur at these wells so long as the gas is not contained, and the gas production does not increase over current levels. The two artesian wells, which according to the best records available should penetrate the 1100-foot Sandstone, probably act as pressure relief wells in that formation.

Current Regulations

Drilling and completion of oil and gas wells in the study area are regulated by the COGCC orders and rules and regulations of the City of Greeley. The COGCC requires surface casing to be set 50 feet below the Fox Hills Sandstone, cement to be placed behind the production casing to 300 feet above the Niobrara Formation, and stage cementing in the upper 3000 feet of a hole drilled within 500 feet of a dwelling or building of public assembly

Table 4
OIL AND GAS WELLS DRILLED WITHIN
THE GREELEY CITY LIMITS AS OF 6/15/84
(Source - Colorado Oil and Gas Conservation Commission)

Well No.	Operator	Sec	Twp	Rng	Map Index No.
5 Best Way Paving	Lundvall	2	5N	66W	267
1 East Greeley Land	Amoco	10	5N	66W	218*
1 Aims	Lundvall	10	5N	66W	515
2 Aims	Lundvall	10	5N	66W	517
7 Lundvall	Lundvall	14	5N	66W	516
2 Gilbert	Lundvall	14	5N	66W	None
1 Milliken	Kissinger	15	5N	66W	219*
1-UPRR-Zimmerman	Plains Expl	15	5N	66W	220*
1 Domke	JRC Oil	22	5N	66W	273
2-22 Rutt Adams Heirs	Bellwether	22	6N	66W	410
1-22 Rutt Adams Heirs	Bellwether	22	6N	66W	365
1-22 Mills-Feit	Bellwether	22	6N	66W	363
1-22 Schaefer	Bellwether	22	6N	66W	364
2-22 Schaefer	Bellwether	22	6N	66W	366
1-25 Kissler Amen	Petromax	25	6N	66W	505
1 Car Body Lake	Bellwether	23	6N	66W	367
1-26 Daniel Buxman	Bellwether	26	6N	66W	421
2-26 Payne	KCF Oil	26	6N	66W	426
1-26 H-D Feit	Bellwether	26	6N	66W	423
1-26 Feit Bros	Bellwether	26	6N	66W	422
1-27 Arnbrecht	Bellwether	27	6N	66W	428
1 Leffler	Willett	27	6N	66W	431
2 Feit Bros	Willett	27	6N	66W	430
1-27 Troudt	Bellwether	27	6N	66W	432
1-27 Buxman	Bellwether	27	6N	66W	429
1-33 W. Davis	Bellwether	33	6N	66W	441
1-34 Lowell	Bellwether	34	6N	66W	443
1-34 Bunn	Bellwether	34	6N	66W	442
3-35 Mobile Premix	Bellwether	35	6N	66W	448
1 Cowan Concrete	Willett	35	6N	66W	377*
1-35 Bunn	Bellwether	35	6N	66W	444
2-35 Mobile Premix	Bellwether	35	6N	66W	447
1-35 Flathead	Bellwether	35	6N	66W	445
1-35 Mobile Premix	Bellwether	35	6N	66W	446
1-35 Putnam	Bellwether	35	6N	66W	449
1 Greeley Sand & Gravel	Termo	35	6N	66W	378*
1-36 Flatirons	Bellwether	36	6N	66W	450

*dry and abandoned

within areas of certain platted densities. The City of Greeley requires stage cementing and in addition a mud log to be run for the total depth of wells drilled within the city limits. These regulations, if enforced diligently, should provide assurance that problems will not develop from oil and gas drilling in the city, and that if some unforeseen problem develops in the future, a record of gas occurrence in the wells drilled in the city will be available.

Information Needed for Determination of Hazards

The LaSalle model, which was to have been relied upon to a major extent in this investigation, is not complete, nor is a description of it available in written form. Three State agencies, CGS, COGCC, and OSE, are working on reports which would define the model. The information presented in this report concerning the LaSalle model is a synthesis mainly of verbal discussions we have had with John W. Rold, Director, Colorado Geological Survey; William R. Smith, Director, Colorado Oil and Gas Conservation Commission; and Thomas B. Majors, Petroleum Consultant. The present report is in no way meant to pre-empt the work of State agencies, and it is fully recognized that later reports may present information that modifies this report. The conclusions stated here are ours and do not necessarily reflect those of others.

This investigation has raised a number of important questions, particularly concerning the 1100-foot Sandstone which appears to be a temporary reservoir for Codell gas in the LaSalle area, and which could become a reservoir for Codell gas in the Greeley area. This sandstone also has the potential to become a Codell gas reservoir in other areas. Knowledge of the physical characteristics of the 1100-foot Sandstone in the LaSalle-Greeley area is critical to defining the existance of a gas hazard in the City of Greeley.

VII. REMEDIAL AND(OR) PREVENTIVE MEASURES

Problem Description

A series of existing problems has been defined in Chapter V. The solution to these problems can only be gained with specific work which will provide direct evidence rather than indirect evidence.

It has been concluded (Chapter VI) that no real gas hazard problem exists in Greeley at this time. If rules and orders established by COGCC and City of Greeley regulations are followed explicitly, it is not likely that problems will develop, with two possible exceptions that can be identified at this time. The first exception is that Codell gas, which apparently is in the 1100-foot Sandstone or higher reservoir in the LaSalle area, could migrate into the Greeley area in the subsurface. A determination of this possibility can only be made by a drilling exploration program.

The second exception is that casing leaks could develop in oil and gas wells which were drilled before the requirement was made to stage-cement the annulus between the production casing and the formation in the 3000 feet of the well, or in wells in which that procedure is improperly carried out.

Regulations

Colorado Oil and Gas Conservation Commission regulations, as recently promulgated, appear to be adequate to ensure the safety of newly drilled wells. The on-going monitoring program, rigorously pursued, should point up problems in old wells in a timely manner, and the required remedial measures can be taken before any damage occurs from new problems in old wells. But the program must be continuous and any anomalous data must be acted upon quickly.

We would prefer to have mud logging and total well bond logging added to the requirements. This would not only add to the data base for further investigations, but would enhance the safety factor against leaky casings or cement.

The regulations of the State Engineer in regard to abandoning water wells appear to be adequate. We cannot comment upon the completeness of enforcement.

The City of Greeley has strengthened its regulations recently to ensure the safety of the population. The only additional regulation which we would suggest is the requirement of bond logs for all cemented sections of a well.

Actions Taken During Investigation

Soon after the first LaSalle event, the City of Greeley placed a moratorium on further drilling for oil or gas within the city limits. The moratorium was extended several times while the City officials consulted with industry representatives, governmental personnel, and other knowledgeable persons regarding steps which could be taken to ensure public safety. On May 1, 1984, the moratorium was lifted, but a requirement that surface casing would be cemented from 3000 feet to the surface of the ground was put into effect.

In the meantime, the COGCC promulgated new regulations for the area covered by Townships 4 through 7 North, and Ranges 64 through E-1/2 68 West. Those regulations applied to wells drilled within 500 feet of a residential area with an existing or platted density of two acres per dwelling or greater, within 500 feet of a dwelling, or within 500 feet of a building of public assembly. They specified that such wells shall be stage cemented between the production casing and the drilled hole from a depth of about 3000 feet to the surface of the ground, or at least 100 feet into the surface casing.

The City canvassed a number of sources to obtain opinions as to the relative safety of the 3000 feet of surface casing as compared with 3000 feet of stage-cemented casing. The concensus was that the two methods would be equally effective if properly carried out. On August 17, the City amended its regulation to require adherence to the COGCC regulation.

In addition to stage cementing, we recommended that the City regulations also require mud logging on oil or gas wells drilled, to detect the presence of gas in any zone cut by the bore hole. The reasons for that

recommendation were several-fold. It is important to the City to establish a data base of gas-related information to use in future investigations. It is also important to be able to: 1) predict where gas might be encountered in future water well drilling and 2) determine whether existing water wells might cut zones which contain gas that might be vented to the surface. The logging is required not only to detect the presence of gas, but to identify the components of the gas. That knowledge would be useful to give an indication of the source of the gas.

If properly adhered to, the existing rules and regulations of both the COGCC and the City of Greeley should ensure safe completion and operation of all wells drilled under these requirements. The wells drilled in the City of Greeley prior to the promulgation of current rules and regulations present a special case. It appears most practical to require regular monitoring of gas pressures in these wells throughout their productive life. In the event that pressures exceed safe limits as determined by the COGCC, remedial actions as specified by that body should be instituted promptly.

VIII. RECOMMENDATIONS

Because of the questions still without satisfactory answers, investigations should be continued.

- Both the 7th Street and 10th Avenue wells found in the Greeley area should be explored, the point of entry of gas into the wells should be identified, and the total depths of these wells should be determined.

- The 7th Street and 10th Avenue wells in Greeley and the wells and vents in LaSalle should be monitored on a periodic basis and the gas analyzed to detect any change in its composition.

- A further effort should be made to attempt to locate the remaining deep artesian wells in Greeley. If any other gas is found venting, it should be analyzed and the source continually monitored.

- The State Oil and Gas Conservation Commission intends to continue its program of monitoring annulus pressures, requiring remedial work when necessary, and promulgating additional regulations to ensure public safety as needed. The City should acquire the data gathered in that program and request notification from the Commission of any remedial action resulting from it within a distance of two miles from the city limits.

- Records and data from petroleum development and from monitoring activities should be examined promptly by qualified personnel upon receipt and catalogued for quick retrieval if necessary.

- Several wells should be drilled and developed in the 1100-foot Sandstone. These wells would be multi-purposed. First would be determining the physical characteristics of the zone through coring, logging, and appropriate testing. Second, the presence of gas would be checked, and if any is found, analyzed to ascertain the source. The wells would then be used as monitoring points to detect any movement or

change in composition of gas which may occur. The wells would also act as vents for any gas which might move into the sandstone.

- o A bond log should be required for cemented portions of any wells drilled within or near the built-up areas.

- o The City should make the necessary arrangements with the State Engineer that water well drillers in the area would be warned of the possibility of encountering high pressure gas in the 1100-foot and other sandstones.

- o The State has adequate regulations regarding procedures to be followed upon abandonment of water wells. Because of the large number of wells and the limited resources available for enforcement, it is not known to what extent those regulations are followed, particularly in old, non-permitted wells. It is recommended that the City meet with the State Engineer to determine how the two entities can cooperate in ensuring that unused wells are properly abandoned.

- o The building code should provide that before any structure is constructed over abandoned wells, it must be demonstrated that the well is adequately plugged; that a venting system will be installed to prevent any possible gas buildup in the well or in the structure; and that a monitoring program will be followed.

IX. CREDITS

Many people and organizations have provided information for this investigation, and to name them all would not be feasible. Likewise, it is infeasible in this report to directly quote every party that provided data. Many more people and organizations could have been contacted if time had been available; however, the number of contacts is felt to be commensurate with the objectives of this report.

Particular thanks go to John W. Rold, Director, Colorado Geological Survey; and to William R. Smith, Director, Colorado Oil and Gas Conservation Commission. Also, thanks are extended to John C. Romero, Chief, Ground Water Analysis Branch, Office of the State Engineer; Thomas B. Majors, Petroleum Consultant; Wes Potter, Director, Environmental Laboratory Services, Weld County Health Department; Dudley D. Rice and Charles M. Threlkeld, U.S. Geological Survey; Bruce Kamada, Mayor of the Town of LaSalle, and his staff; and George Aubrey, Tony Sharp, Roger Hively, and Chuck Fowler, all of Bellwether Exploration Company. Ms. Peggy Ford, Greeley Municipal Museum, provided much historical background.

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Several private citizens also provided information from recollection and from files, as did personnel with Core Laboratories, Inc. and Welex Services.

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PLATES

MISSING